

Search for CP violation in the $B_s^0 - \bar{B}_s^0$ system

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Abstract. We present studies from the LHCb experiment leading to the measurement of the weak phase ϕ_s . At first, flavor tagging is established by measuring the B_s^0 oscillation frequency Δm_s . Then, flavor tagging is used to perform a measurement of the well known CKM angle $\sin 2\beta$ in $B^0 \rightarrow J/\psi K_s^0$, before we constrain ϕ_s through an amplitude analysis of $B_s^0 \rightarrow J/\psi \phi$ decays. These studies use about 35 pb^{-1} of data taken in 2010. In addition, we present the measurement of $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+)$ and the first observation of $B_s^0 \rightarrow J/\psi f_2'(1525)$.

Keywords: CP violation, CKM angle β , ϕ_s , Δm_s , new physics

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INTRODUCTION

Decays of neutral B mesons provide a unique laboratory to study CP violation originating from a weak phase in the CKM matrix. The relative phase between two amplitudes, direct decay and decay after mixing, gives rise to time-dependent CP violation. The decay $B_s^0 \rightarrow J/\psi \phi$ is considered the golden mode for measuring this type of CP violation in the B_s^0 system. In the Standard Model, the CP violating phase in this decay is predicted to be $\phi_s \approx -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. Indirect measurements show $2\beta_s$ is small, $2\beta_s = (0.0363 \pm 0.0017) \text{ rad}$ [1]. But new contributions to $B_s^0 - \bar{B}_s^0$ mixing may alter the expected value of ϕ_s [2, 3]. Previous constraints on ϕ_s at the 0.5 rad level have been reported by the Tevatron experiments CDF [4] and D0 [5]. The precise determination of ϕ_s is one of the key goals of the LHCb experiment [6]. In this letter we present a series of measurements leading the way to a measurement of ϕ_s .

CONSTRAINTS ON ϕ_s

We first present [7] a measurement of the mixing frequency Δm_s of the B_s^0 system, using about 1350 B_s^0 signal candidates reconstructed in 36 pb^{-1} collected in 2010 through their decays $B_s^0 \rightarrow D_s^- \pi$ and $B_s^0 \rightarrow D_s^- 3\pi$, where $D_s^- \rightarrow K^+ K^- \pi^-$. This measurement demonstrates that the achieved decay time resolution (44 fs in $D_s^- \pi$, 36 fs in $D_s^- 3\pi$) is sufficient to resolve the fast oscillations in B_s^0 mixing. It also establishes the flavor tagging algorithms required to identify the B_s^0 flavor at production time. The effective tagging efficiency is $\epsilon_{\text{eff}} = 3.8 \pm 2.1 (\text{stat})\%$. Figure 1 shows the result of an amplitude scan, converging to $\Delta m_s = 17.63 \pm 0.11 (\text{stat}) \pm 0.04 (\text{syst}) \text{ ps}^{-1}$, which is compatible with the Tevatron measurements and of similar precision.

We then [8] make use of the flavor tagging algorithms to repeat the measurement of the CKM angle $\sin 2\beta$, which was determined by the B factories to amazing precision: $\sin 2\beta = 0.673 \pm 0.023$ [9]. In 35 pb^{-1} we find about 280 tagged $B^0 \rightarrow J/\psi K_s^0$ decays, considered the golden channel for this measurement. A maximum likelihood fit to the decay time distribution and the B^0 invariant mass, simultaneously fitting tagged and untagged samples, reports $\sin 2\beta \simeq S = 0.53_{-0.29}^{+0.28} (\text{stat}) \pm 0.05 (\text{syst})$. The systematic uncertainty is dominated by that on the flavor tagging. Although not yet competitive with the result of the B-factories a very precise measurement will be possible with the data that LHCb will collect over the coming few years. Figure 1 shows the time dependent raw asymmetry of B^0 and \bar{B}^0 decaying into $J/\psi K_s^0$, the amplitude of which is proportional to S .

Finally, we perform [10] an untagged angular analysis of $B^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi \phi$ decays. This gives access to the decay amplitudes for both final states, as well as the lifetime and lifetime difference $\Delta\Gamma_s$ for $B_s^0 \rightarrow J/\psi \phi$. Due to the forward geometry of the LHCb detector, the reconstruction efficiency for these decays is a non-trivial function

¹ on behalf of the LHCb collaboration

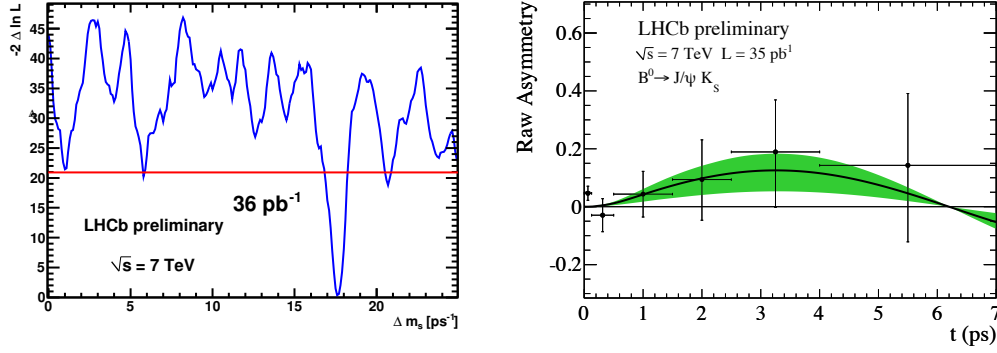


FIGURE 1. Left: Likelihood scan for Δm_s in the range from $[0, 25] \text{ ps}^{-1}$. The horizontal line corresponds to the likelihood value expected for infinitely fast oscillations. Right: Time dependent raw CP asymmetry in $B^0 \rightarrow J/\psi K_s^0$ with the fit projection (signal and background) overlaid. The green band corresponds to the one standard deviation statistical error.

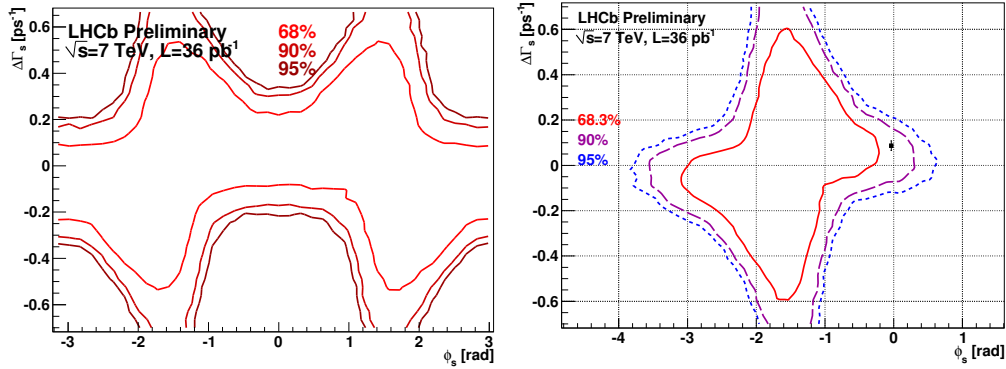


FIGURE 2. Feldman-Cousins confidence regions in the $\Delta\Gamma_s - \phi_s$ plane. The Standard Model estimate is at the black square. Both untagged (left) and tagged (right) analyses of $B_s^0 \rightarrow J/\psi \phi$ decays are shown.

of the decay angles. Then we add [11] the flavor tagging information to the measurement. In the 36 pb^{-1} of 2010 we find approximately 760 $B_s^0 \rightarrow J/\psi \phi$ events. We extract constraints on ϕ_s through a maximum likelihood fit to the decay time distribution, the B_s^0 invariant mass, and three decay angles. The data sample is too small to allow for meaningful point estimates. Instead we perform a Feldman-Cousins analysis which gives contours in the $\Delta\Gamma_s - \phi_s$ plane (Figure 2) that have frequentist coverage. We observe a deviation from the Standard Model of 1.2σ , and constrain $\phi_s \in [-2.7, -0.5] \text{ rad}$ at the 68.3% confidence level.

ANALYSIS OF $B_s^0 \rightarrow J/\psi(KK, \pi\pi)$

Following our recent first observation of the $B_s^0 \rightarrow J/\psi f_0$ decay [12], we update [13] the analysis of the $B_s^0 \rightarrow J/\psi \pi\pi$ final state with a larger dataset of 162 pb^{-1} , coming mostly from the first period of the 2011 run. We also show that the f_0 resonance is consistent with being purely S -wave, making $J/\psi f_0$ a pure CP odd eigenstate. This will allow for a measurement of ϕ_s in $B_s^0 \rightarrow J/\psi f_0$ decays without the need of an amplitude analysis. We measure the ratio of rates in a $\pm 90 \text{ MeV}/c^2$ mass window around the $f_0(980)$, $R_{\text{effective}}^{f_0} = \mathcal{B}(B_s^0 \rightarrow J/\psi f_0, f_0 \rightarrow \pi\pi) / \mathcal{B}(B_s^0 \rightarrow J/\psi \phi, \phi \rightarrow KK)$, to be $R_{\text{effective}}^{f_0} = (21.7 \pm 1.1(\text{stat}) \pm 0.7(\text{syst}))\%$.

We extend our analysis to the $B_s^0 \rightarrow J/\psi K^+ K^-$ final state. In the $K^+ K^-$ invariant mass spectrum we for the first time observe, in addition to the $\phi(1020)$ component, a structure that we identify as the spin-2 $f_2'(1525)$. An angular analysis confirms, that the data are consistent with the spin-2, and inconsistent with the spin-0 hypothesis. The $B_s^0 \rightarrow J/\psi f_2'$ mode can also be used to measure ϕ_s , although here a transversity analysis would be required as in $J/\psi \phi$. It is also

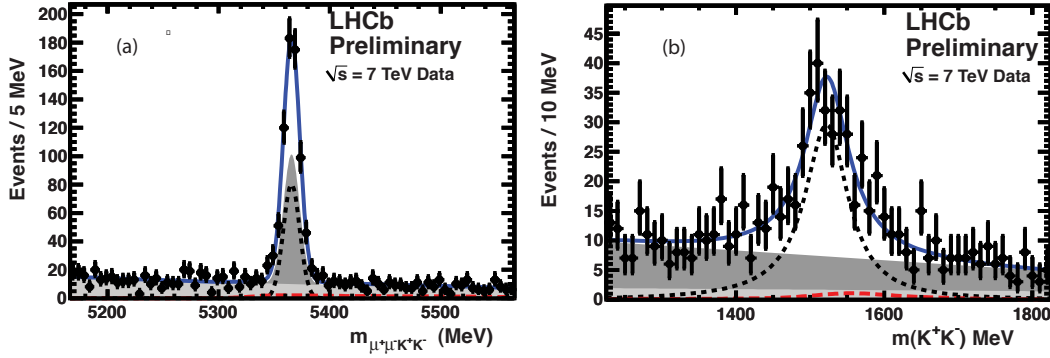


FIGURE 3. The $J/\psi K^+ K^-$ (a) and the $K^+ K^-$ (b) invariant mass spectra showing peaks of the B_s^0 and, for the first time in this mode, the $f_2'(1525)$ (short dashed). Shown are the combinatorial background (light grey), non-resonant $J/\psi K^+ K^-$ (dark grey), $B^0 \rightarrow J/\psi K^- \pi^+$ background (long-dashed).

possible that this mode could be used to resolve ambiguities in ϕ_s if the interference with non-resonant $J/\psi K^+ K^-$ is significant. Figure 3 shows both the $J/\psi K^+ K^-$ and the $K^+ K^-$ invariant mass spectra for this first observation. We measure $R_{\text{effective}}^{f_2'} = (19.4 \pm 1.8(\text{stat}) \pm 1.1(\text{syst}))\%$ in a $\pm 125 \text{ MeV}/c^2$ mass window around the f_2' .

MEASUREMENT OF $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+)$

We also analyze [14] the $B^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ decay channels, of which the latter plays an important role in the calibration of the flavor tagging algorithms. In 37 pb^{-1} we measure the ratio of their branching fractions to be $\mathcal{B}(B^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (3.94 \pm 0.39(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-2}$. This result has a precision comparable to the present world average [15], but is lower by 2.2σ .

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